CRITICAL PARAMETERS FOR HIGH SPEED DATA ON SLIP RINGS

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INTRODUCTION

Many applications require rotary platforms and slip rings to carry electrical power and signals to and from the rotating system. Standard slip ring technology involves forming an electrical path with rotating rings contacted by a stationary sliding contact or brush. In the world of analog signals, analog video, and low speed digital data, the specification of a slip ring for a set of signals and power involved specifying the voltage and current required for the electrical signals and or/power. However, in the new world of digital video, high speed data, and networking, slip ring design issues have move out of the DC regime and the requirements involve bandwidth. The good news is that there are slip ring options available for digital video and high speed data. This application note is intended to assist the reader in understanding slip rings used for high speed digital applications.

This application note will first discuss the parameters that have the greatest impact on the performance of high speed data on copper transmission lines. Then specific slip ring parameters will be discussed to provide some insight into the major factors that affect slip ring performance in high speed copper data lines. The biggest change in slip ring technology over the past 15 years is in the understanding of the critical design parameters required for handling digital data

HIGH-SPEED DATA AND PHYSICAL MEDIA

The decision to use copper or fiber as the transmission line media is one of the most critical that a system designer must make. The advantages of fiber are well documented and include EMI/EMC immunity, virtually unlimited bandwidth, and light weight. However, copper offers environmental robustness, simpler interfaces, easier field repair, and normally lower cost. A number of factors go into the fiber/copper decision, but the important question is whether the anticipated data rate exceeds the bandwidth limit of the copper transmission line.

A good place to start is to understand the maximum length of copper transmission line that can support the chosen data format. Table 1 summarizes the guidelines for various high-speed data formats. This table considers the lossy characteristics from any transmission line (attenuation, amplitude distortion, phase distortion) and relates these losses and distortions to the ability of the data format to tolerate or compensate these affects. Digital data is typically transmitted on cable with controlled impedance lines. Since most data is transmitted differentially, these cables are typically twisted pairs. Normally the impedance of the cable is specified in the format specification and the higher the bandwidth the more important it is to control the cable impedance.

It is important to note that the bandwidth requirements of this table reflect not only the bandwidth capabilities of the cabling and the data rate of the signal but also the ability of the electronics associated with specific data formats to compensate for transmission line loses and mismatching. Specifically, it is important to note that firewire (IEEE 1394) and USB 2.0 have very short transmission line guidelines. These two formats were designed for computer peripherals and communication. Neither were designed for long cable connections and are very sensitive to long cable lengths or any impedance mismatched components place in the transmission line such as connectors or slip rings. On the other hand, the two SMPTE formats also illustrate the benefit of active cable equalizer electronics used to compensate for cable losses and phase delay.

TABLE1: Cable Length Guidelines for Data Formats

Data Format	Media or Speed	Length
10BASE2	RG58 coax	185m
100BASE-TX	EIA/TIA Category 5 unshielded twisted pair (2 pair)	100m
1000BASE-T	Cat 5 UTP (4 pair)	100m
1000BASE-CX	Twinax cable	25m
IEEE-1394	400 Mb/s	4.5m
IEEE-1394b	Beta 800; 800 Mb/s	4.5 m
Fibre Channel	1062.5 Mb/s	30m
Hotlink	400 Mb/s	50m
SMPTE 259M	270 Mb/s	300m
SMPTE 292M	1485 Mb/s	150m
USB 2.0	480 Mb/s	5 m

Discontinuities in the transmission line at connectors and other terminations have a degrading effect on the performance, so the overall transmission line characteristics must be evaluated before a final determination on a final configuration can be made. System designers often treat terminations as equivalent length of cable in terms of this degrading effect. This is a very subjective method, but probably the best available. The analysis that Moog typically uses to ensure that its hardware does not have a significant impact on the effective length of transmission length is the "quarter wave length analysis".

This quarter wave analysis looks at the effect of any impedance discontinuity on the bandwidth of the transmission line, i.e., the maximum signal frequency that can be transmitted on the transmission line. Transmission line theory tells us that if an impedance mismatch in a transmission line is close to ¼ of the wave length of the signal then significant signal attenuation and distortion can occur. These losses are due to signal reflections and standing waves on the transmission line. Therefore in the determination of the effect of any mismatch inserted into a high speed data line, it is important to understand the total length of the discontinuity and the relationship this length to the wavelength of the signal frequency. When this length approaches ¼ of the wavelength of the signal frequency being carried on the transmission line, the signal begins to degrade beyond acceptable limits. In the case of slip rings, we refer to this ¼ wave length as the bandwidth limit of the slip ring.

This quarter wave analysis is a worst case analysis since it does not take into effect that closely matching the transmission line impedance can significantly improve the bandwidth of the device by minimizing the ¼ wave effect. However, in the absence of actual test data the ¼ wave analysis can provide a conservative estimate.

Data Bandwidth

The short discussion above outlines the considerations for determining the bandwidth of the physical media, i.e., the cable in the case of copper transmission lines. What methods do we use to determine the bandwidth required by the digital data being transmitted? The transmission line analysis strategies used above refer to signal frequencies as if these signals are sine waves. However digital data are normally square waves. The first problem is to understand how to discuss digital data in the frequency domain.

Digital data is a series of voltage shifts (ideally instantaneous) that represents logic shifts (of ones and zeros). Fourier theory shows that these resultant square waves can be represented by a series of sine waves using a Fourier series approximation. Figure 1 shows a square wave approximated by the 1st, 5th, 11th, and 49th fundamental frequency.

Data transferred as 1's and 0's at a specific Megabits/sec (Mbps) rate has a first harmonic of (Mbps/2) Mhz. Under normal circumstances, transferring the fundamental frequency and the first two odd harmonics will normally reproduce the square wave pattern very, well as shown by the second graph of Figure 1 (i.e.,, K=5). When transmission lines are analyzed for their ability to transmit digital data, the transmission line "bandwidth" refers to the maximum frequency that can be transmitted on the line without "unacceptable" signal degradation which is ultimately evaluated as a bit error rate (BER) that is unacceptable for the specific application. It is important to point out that bandwidth does not equal data speed, but it can be related to data speed using these Fourier relationships. Moog engineers have found that maintaining a bandwidth of at least the 3rd harmonic of the fundamental frequency of the data provides a signal transfer of acceptable quality in real world situations.

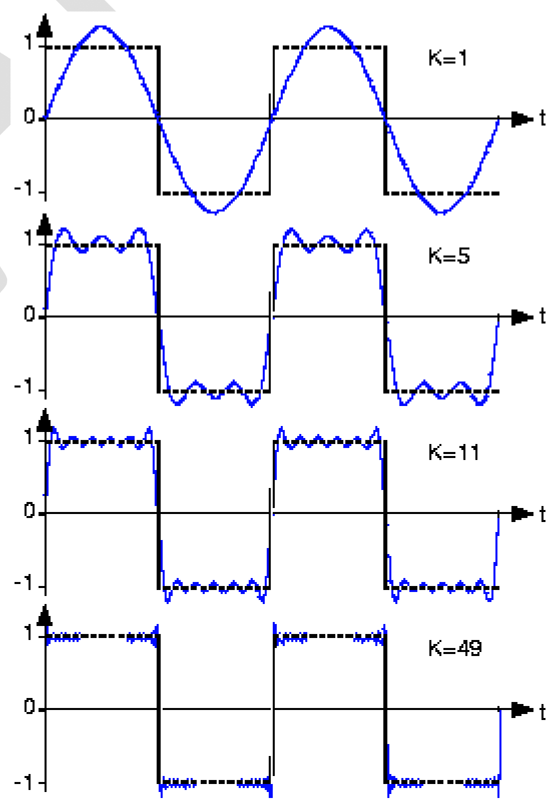

Figure 1: Fourier Series Approximation of a Square Wave

The bandwidth analysis can become more complicated when features like encoding patterns come into play. The matter of encoding and its relationship to the bit rate of digital data is important and can be illustrated by looking at actual data. Figure 2 shows the frequency components of output from Cypress Hotlink II running at 150 Mbps. The horizontal axis shows frequency (150 MHz/ div). The energy peaks at 75, 225, and 375 show the fundamental (75 MHz) and the odd harmonics. So at least 225 MHz of bandwidth (third harmonic) is sufficient for a good signal quality as predicted by our analysis above and 375 would be ideal. But before we make the conclusion that 225 MHz of bandwidth is required to transfer 150 Mbps of data consider 100 BaseT Ethernet.

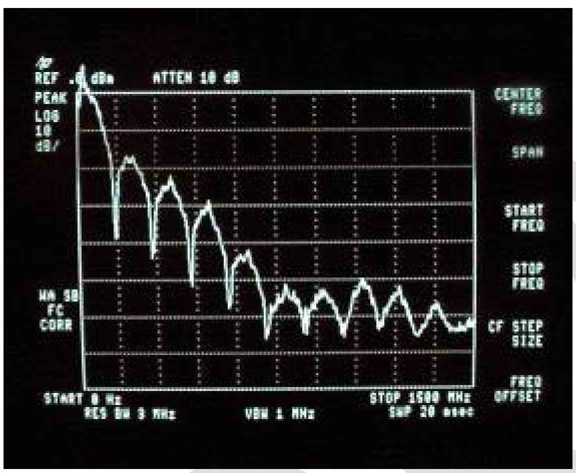

Figure 2: Frequency Spectrum of 150 Mbps Hotlink

In contrast to the signal of Figure 2, Figure 3 shows the frequency components of a 100 BaseT Ethernet signal up to 500 MHz. Ethernet uses a unique encoding scheme that allows 100 BaseT to transmit 100 Mbps worth of data using a 25 Mbps square wave. In terms of signal fidelity, a bandwidth of 100 MHz passes 99% of the energy of the Ethernet signal and gives excellent signal fidelity. This "more data per bandwidth" is one of the advantages of Ethernet.

We can carry this analysis even further by looking at the spectrum for 1000 BaseT (Gigabit) Ethernet. The goal of the IEEE P802.3 Task Force was to allow 1000 BaseT to be implemented on existing media infrastructure. 1000 BaseT utilizes all four twisted pairs of CAT 5 or CAT 6 cable. Therefore it should not be a surprise to see that Figure 4, a frequency spectrum of a 1000 BaseT signal is almost identical to Figure 3. This similarity means the bandwidth requirements for each pair of a 100BaseT signal are almost precisely that of a 100 BaseT signal pair. There are other critical characteristics of GigE signals that place constraints on the transmission and these are discussed in Appendix 2 which provides a more detailed discussion of 1000 Base-T Ethernet or GigE.

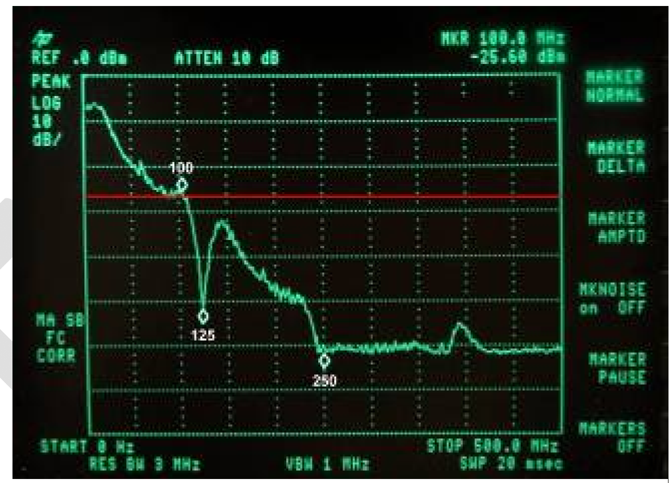

Figure 3: Frequency Spectrum of 100 BASE Ethernet

These figures should illustrate that it is important to understand the actual Baud rate of the data signal to approximate the bandwidth. Another commonly used method of evaluating bandwidth, if the rise time(T_r) of the digital square wave is known, is to express the bandwidth by using a Nyquist approximation:

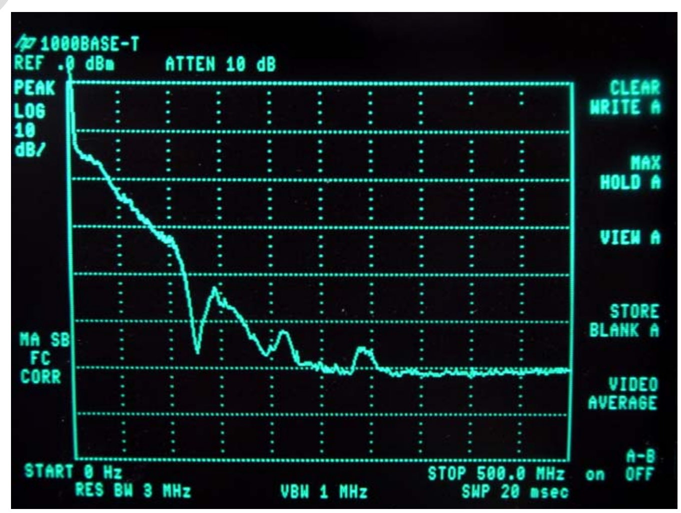

Figure 4: Frequency Spectrum of Gigabit Ethernet (1000 Base-T)

$$BW = {}^{0.5}/_{Tr}$$

This equation typically produces results similar to the Fourier analysis, but the rise time analysis can give more representative results in the case of data with very fast rise time requirements and fairly infrequent pulses.

There are a number of other very important parameters that must be considered when evaluating the ability of a transmission line to transmit high speed digital data, such as crosstalk, shielding, and phase delay. We will consider these parameters specifically in the discussion on slip ring performance parameters.

SLIP RING PERFORMANCE PARAMETERS

What are the important parameters to understand when reviewing a transmission line component, specifically a slip ring, for suitability for high speed data or high definition digital video signals? As the previous discussion outlined, the primary task is to compare the bandwidth capability of the slip ring with the bandwidth requirements of the data. Broadband slip ring designs are now able to successfully transmit data up to 1.5 Gbps in a passive device and up to 5 Gbps with some signal conditioning. Addressing the question of high-speed data through slip rings requires some discussion of the critical performance parameters. The most important parameters that limit the speed of digital data in slip rings are: bandwidth, crosstalk, and EMI/EMC (shielding).

Bandwidth

A slip ring represents a discontinuity, or perturbation, in a transmission line as a result of an impedance mismatch of the rings and brushes and the transmission line. The degree to which the impedance of the rings and brushes can be matched to the impedance of the transmission line and the effective length of discontinuity are the best indicator of how effective the slip ring will transmit high-speed data. Various micro-stripline design techniques have been adopted to match the slip ring impedance to the line impedance. Although these stripline techniques allow the slip ring designer to approximate the transmission line impedance, it is impossible to perfectly match this impedance. The goal is to minimize the mismatch as well as the length of the mismatch.

Since the mismatch length is the most critical parameter, the slip ring diameter has a significant effect on the bandwidth of a slip ring and larger diameter rings typically have lower bandwidth capability. If we consider the slip ring to be a discontinuity in the copper transmission line, this diameter effect can be understood as a fraction of the wavelength of the signal's bandwidth. As discussed earlier, when the length of an impedance discontinuity approaches ¼ of the signal bandwidth, the signal quality becomes compromised:

$$L = c * \vartheta p /_{(4 * f)}$$

Where: L=critical path length
c=speed of light vacuum
ϑp = velocity of propagation factor (~ 0.6)
f= signal bandwidth

In the case of 500 MHz bandwidth for example, the critical length (1/4 wavelength) is 9 cm. This means that any transmission line discontinuity or perturbation of length greater than 9 cm will begin to have a significant impact on signal quality. This 9 cm length equates to 2.87 cm diameter.

How do we get from this critical bandwidth to a maximum Baud rate that can be transferred over the slip ring?

1. Find the frequency that has as ¼ of its wavelength the maximum signal path in the slip ring (length of discontinuity). This frequency is the fundamental frequency of the bandwidth of the slip ring (or the media). We know however that there are harmonics of this fundamental frequency that are critical and the media must also support those.
2. Divide the fundamental frequency by three to find the frequency of the signal that is the third harmonic that should be transmitted on the slip ring without excessive attenuation. This is the maximum signal bandwidth.
3. Multiply this frequency by 2 to derive the baud rate corresponding to this maximum signal bandwidth

This estimate is a worst case analysis since the assumption is that nothing has been done to ameliorate the impedance mismatch. Figure 5 provides a graph of these calculations for the standard Moog commercial slip rings. Using the equation of page 4, we can estimate the effect of diameter on the bandwidth limit of slip rings. These calculations assume that the transmission line cable is terminated within ½ inch of the rings and brushes inside the slip ring capsule itself, thereby minimizing the effect of cable mismatches. Moog Application Note 228 discusses the bandwidth of commercial slip rings with these diameters in more detail.

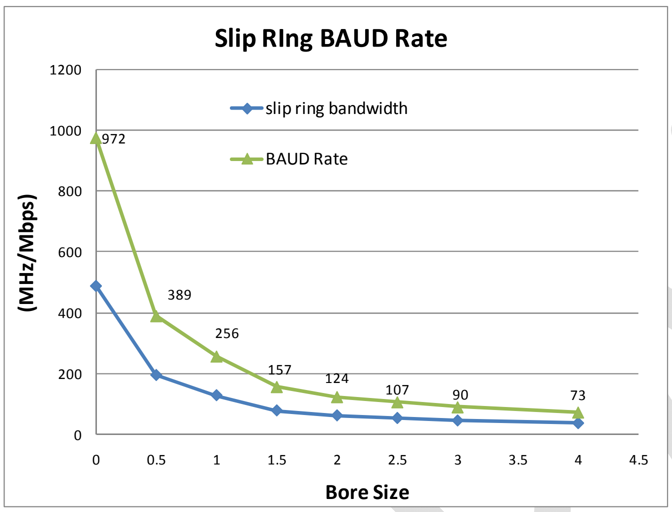

Figure 5: Bandwidth Limit of Slip rings as a funtion of Bore Size

This length (or diameter) effect can be minimized by minimizing the impedance mismatch between the discontinuity and the transmission line, but it is impossible to completely eliminate. The two insertion loss plots of Figure 6 are of data channels that are identical except for diameter. The top rings are approximately 6.4 cm in diameter and the rings in the bottom chart are approximately 15 cm in diameter. The critical diameter calculations graphed above would tell us that these rings would have a bandwidth of about 220 MHz and 95 MHz respectively. However impedance matching of the rings to the transmission line allows extension of the bandwidth to 800 and 600 MHz respectively. However the charts do illustrate that diameter is still an important consideration.

We can use the graphs of Figure 6 to illustrate how Moog engineers use actual measured bandwidth values (typically insertion loss vs. frequency) to evaluate the

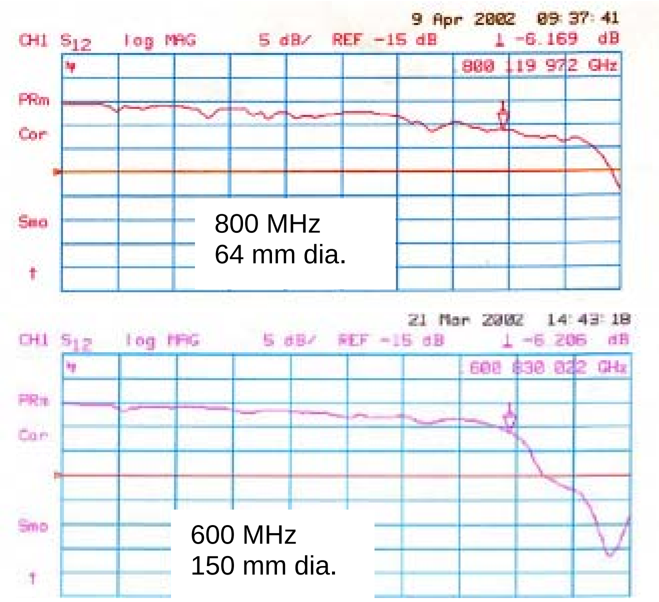

Figure 6: Insertion loss vs. frequency for two different diameter ring pairs

data rate capability of a specific slip ring design. If we assume that the data rate must have its 3rd harmonic below the -6 dB loss marker on each graph the data rate that can be transmitted on these two ring pairs is 533 Mbps (800 MHz) and 400 Mbps (600 MHz).

Frequency resonances resulting from impedance discontinuities will cause time domain distortions called "group delay". This spreading of the edges of the square waves across the time domain results in the received data rise and fall times having edge jitter or amplitude jitter. Jitter is normally measured as an "eye pattern", and these eye patterns are often used to determine if a transmission line will transmit a specific data signal with an acceptable bit error rate (BER).

Figure 9 shows an eye pattern of an IEEE 1394 B (Firwire-800 Mbps) signal transmitted through a slip ring showing the 1394 B mask for an acceptable eye opening This mask appears as the black diamond in the center of the eye and the black bars at the top and bottom of the pattern. The size of the eye pattern opening can be correlated to BER. A more restrictive eye mask correlates to a higher BER. Since eye patterns are often quicker tests to run than BER tests and they provide more diagnostic information than BER tests, eye patterns are universally used to communicate the ability of a specific circuit or transmission line to handle digital data. Data specifications typically contain eye pattern masks that must be satisfied for successful data transmission.

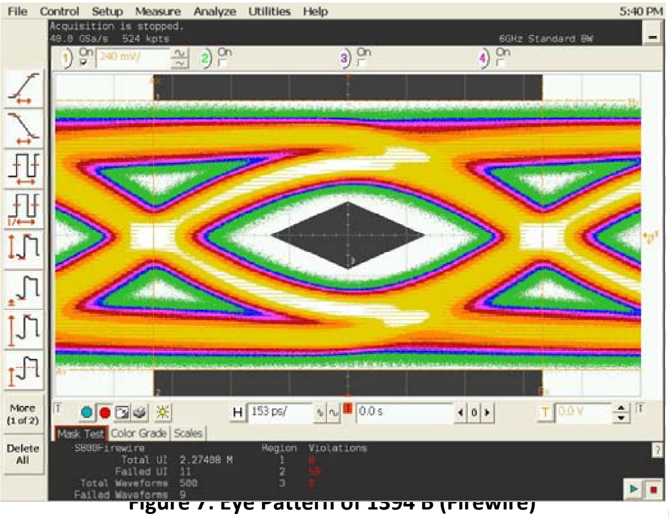

Figure 7: Eye Pattern of 1394 B (Firewire)

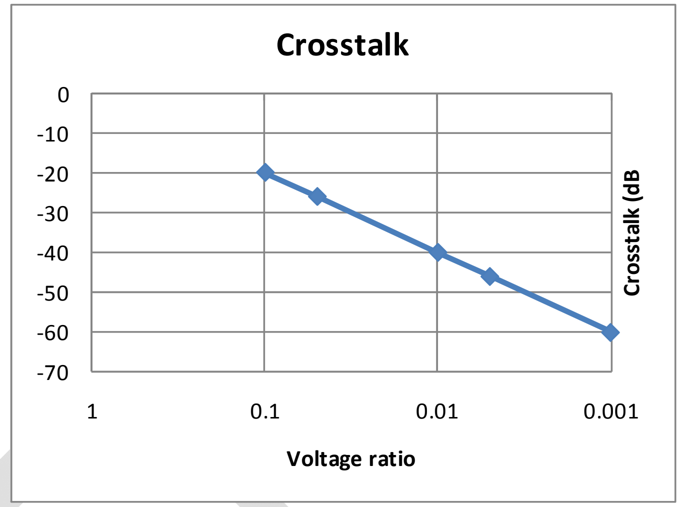

Figure 8: Crosstalk and frenquecy

Table 2 shows three of the most common methods of determining if the bandwidth of the transmission line is sufficient to transmit the desired data rate.

Table 2: Bandwidth Measurements

Test	Parameter measured	Advantage
Insertion loss	Insertion loss over the frequency of interest	Provides attenuation and a snapshot of resonant frequencies to assist in design
Eye Pattern	Data jitter	Provides diagnostic signal quality information at the data speed in question
BER	Bit error rate over time	Provides go/no-go information about data quality over time.

Crosstalk

Bandwidth is not the only parameter of concern when dealing with high speed data in slip rings. Second to the bandwidth in evaluating the ability of a slip ring to transmit high-speed digital data is crosstalk. Crosstalk (in dB) between a noise emitting channel V1 and a noise sensitive channel, V2, is:

$$X_{TK}(dB) = 20\log\frac{V_2}{V_1}$$

This relationship is shown graphically in Figure 8.

When a number of channels are incorporated into a relatively small physical package, capacitive coupling is the ***primary*** cause of this crosstalk. The relationship that governs crosstalk (Kc expressed in dB) from a primary, or emitting, circuit, to a capacitively coupled circuit, when the frequency (f) and capacitance (C) are known is:

$$Kc = 20\log(2\pi f C)$$

Figure 9 shows an example of crosstalk between two data rings prior to several design changes to improve the crosstalk performance. This graph shows that the relationship of crosstalk to frequency is more complex than strictly linear (on a log scale) as predicted by the equation above. Other factors are at work besides capacitive coupling. This graph suggests by its bimodal appearance that two resonant frequencies at 200 and 400 MHz are generating significant EM radiation, which is being coupled into the susceptible circuit. The solution to this problem goes back to ensuring that the slip ring has the appropriate bandwidth. The standing waves and resonances that create the bandwidth limitation of high speed signals also generate the resonant frequencies of high EM radiation and radiation coupling.

It is important to evaluate the crosstalk requirements of a high speed slip ring properly. High speed data lines are the greatest risk of being noise emitters due to their high frequency components. The primary frequency of this noise is the fundamental frequency of the data. For example 100 Mbps data has a fundamental frequency of 50 MHz and it is at this frequency that the greatest crosstalk will occur. There is some coupling at the odd harmonics (3rd, 5th, etc.), but this coupling is of secondary effect.

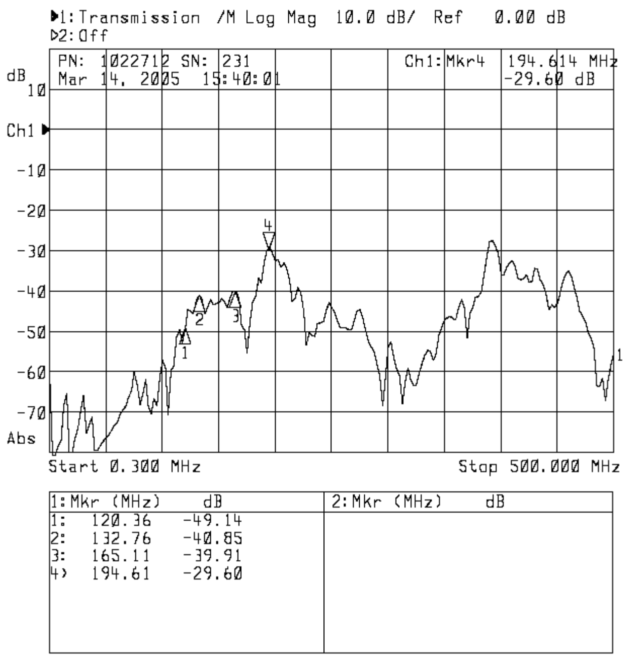

Figure 9: Crosstalk vs. frequency in slip ring assemblies

Inductive coupling can have an effect in the coupling of noise into sensitive signals circuits in the case of power circuits with very high switching frequencies or sharp surge spikes, i.e., very large $\frac{di}{dt}$. However, inductive effects are almost always secondary effects and are normally handled by using care in isolating sensitive signals from power as much as possible using physical distance.

The risk of the crosstalk from digital lines is primarily to sensitive low level analog signals. As the graph of Figure 8 shows, a 5 volt digital signal with -40dB crosstalk will produce 50 mV (i.e., 5 V x .01) of crosstalk noise. This could be a significant noise contributor to a low level analog signal (analog video for example). On the other hand, 50 mV is relatively insignificant on a data channel, especially differential data since this crosstalk will normally not be seen as differential noise. It is also important to consider the frequency of the crosstalk noise. As stated earlier, this noise will be primarily the fundamental frequency of the data line, which can often be filtered on analog channels.

EMI

Electro-magnetic interference (EMI) is the final performance parameter that should be highlighted in regards to high-speed data and slip rings. Because of the high frequency components of high rate data transmission lines, it is important that proper shielding and grounding principles be applied at the rotational interface. Specifically a low impedance ground path should be maintained at each rotational interface and all shields must maintain their continuity and proper reference level to ground through the interface. The slip ring should be designed to be a Faraday cage to prevent EMI leakage into or out of the housed contacts and EMI sealing techniques should be used that are appropriate to the specified frequencies. And finally proper cable termination practices are important at all cable terminations with a clear definition of shield termination strategies and techniques. Proper utilization of these techniques will allow slip ring assemblies to meet even the harshest EMI/EMC requirements.

The magnifying effects of slip ring resonances and standing waves were discussed in the crosstalk section, but these effects are also part of the overall effect on the EMI performance of the slip ring.

The Effect of Rotation

What is the effect of rotation on the performance of slip rings at high data rates? The issue that first comes to mind is the effect of contact noise on the signal. This contact noise is a small variation in resistance that is produced by resistance changes that occur at the point of contact between the rotating ring and the stationary brushes. Typically there are at least two brush contacts to reduce this resistance change. Slip ring contacts are normally precious metal to prevent the formation of high resistance oxidation films and very small amounts of contact lubricant prevent the formation of uncontrolled, high resistance organic films. Contact resistance variation is normally 10 to 40 milliohms/ revolution when a slip ring is rotated between 10 and 120 RPM. Since the current level of a digital signal is normally around 20 milliamps, this 10-40 milliohm value represent 0.2 to 0.8 microvolts of noise. This equates to -75 dB of noise on a 5 volt circuit. Since it is common to see -40 dB or more of crosstalk noise, -75 dB of contact noise is inconsequential. As a matter of fact, the contact noise has to get close to one volt to start to have the same order of magnitude effect as crosstalk.

A more significant effect of rotation on digital data is the change of the effective length of the discontinuity of the slip ring. Wire or cable is typically terminated to the ring in one radial location on the ring. When the brush contact rotates around the ring, the length the signal travels from the lead termination to the brush varies as the brush changes location with variation. This variation has an effect on the bandwidth of the slip ring, and depending on the diameter this effect can be significant. This effect can be counteracted by terminating leads at multiple locations on the ring, but normally the bandwidth is simply calculated at the worst case location of the lead termination.

Case Study: Data on 0.5 diameter Slip Ring SRA-73683

Pictured below is a SRA-73683 commercial slip ring with a 0.5 inch through-bore. Testing was performed on this slip ring to confirm the bandwidth estimations calculated using the guidelines of this Application Note.

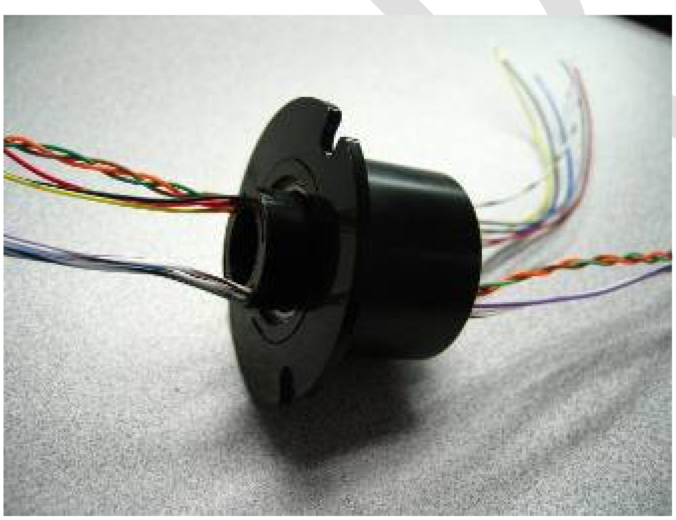

Figure 10: SRA-73683 Slip Ring

Figure 10 shows insertion loss data from the 0.5 inch bore slipring. The picture of the unit shows that the

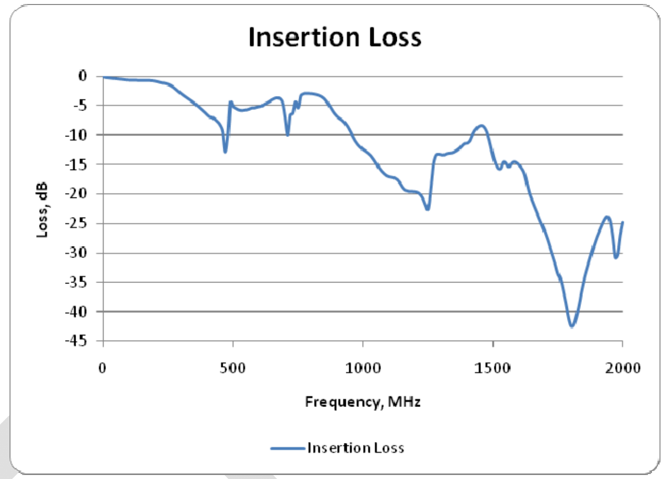

Figure 11 : SRA-73683 (0.5 bore) slip ring bandwidth

cable was twisted up to the exit point of the slip ring, but the wire was not twisted inside the unit. This is a very short unit so this lack of internal twisting likely won't have a big impact. If Figure 5 is used to estimate the bandwidth limit of a 0.5 through bore slip ring, the value is approximately 200 MHz. The insertion loss data of Figure 9 suggests that the -6 dB value of this slip ring configuration is approximately 300 MH, but the data also shows that the roll-off starts at approximately 200 MHz. The data show that the resonances in transmission line are complex and there is little value in trying to look past the -6 dB point. This data, along with other tests, and evaluation lead us to the conclusion that the estimates represented by Figure 5 are somewhat conservative and useful method of predicting usable bandwidth of a slip ring of known diameter.

Figure 11 highlights the effect of bandwidth limitations even better. This attenuation is the effect of mismatch losses associated with impedance mismatches in the transmission line. Again, it should be noted that the roll-off starts again at around 200 Mhz.

A look at crosstalk data also highlights the need for using a slip ring with the appropriate bandwidth. Figure 12 shows the differential crosstalk between circuit pairs as a function of frequency. We see the familiar frequencies showing up as crosstalk peaks. The same resonance nulls that play havoc with the bandwidth result in EM radiation that can be coupled to other circuits. This is in addition to the capacitive coupling that can be predicted from the circuit capacitance.

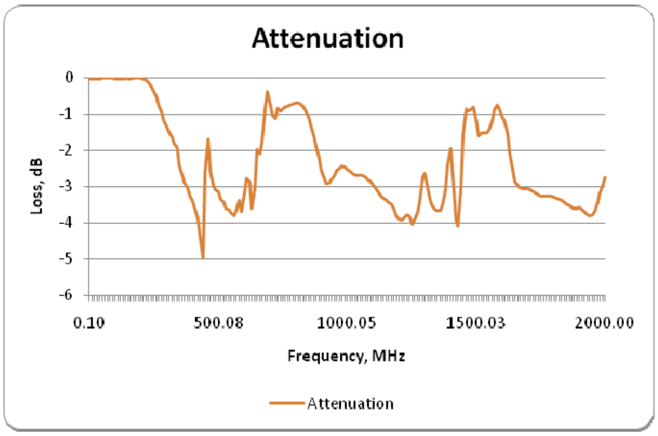

Figure 12 : Attenuation vs Frequency (SRA 73683)

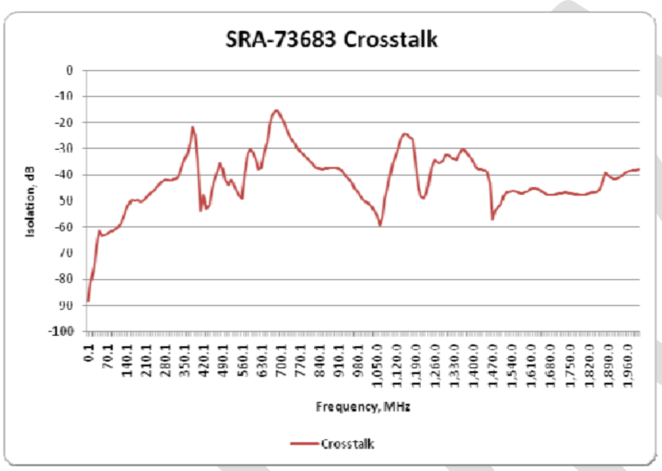

Figure 13 : Crosstalk vs Frequency

The 200 MHz bandwidth limit suggests that the maximum data we should put across this ring is 400 Mbps. Figures 14 and 15 show eye patterns for 500 and 800 Mbps data streams. The eye diagram is used to analyze the quality of a digital signal. The eye diagram plot provides a qualitative and quantitative description of system performance and is obtained by overlapping multiple cycles of the signal on the screen of an oscilloscope. The eye opening/closure is indicative of the signal integrity. The deviation of the signal crossing shows the jitter in the signal and its complement. A larger eye opening lowers the probability of bit errors.

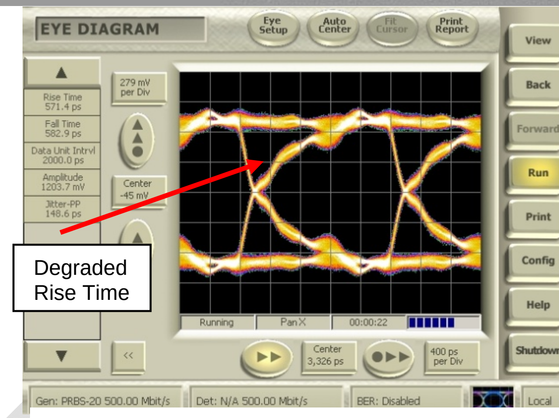

Figure 14: 500 Mbps data transfer

Figure 14 shows the 500 Mbps rise time. The “eye” is relatively open with little jitter, but the leading edge rise time degradation is fairly significant ,likely the result of the attention at starts at around 350 MHz. However, this eye pattern would likely be acceptable for 500 Mbps data, and the conclusion is that 500 MBaud is the maximum data rate of this slip ring with this wiring configuration. The eye pattern at 800 MHz shows an even more pronounced edge degradation.

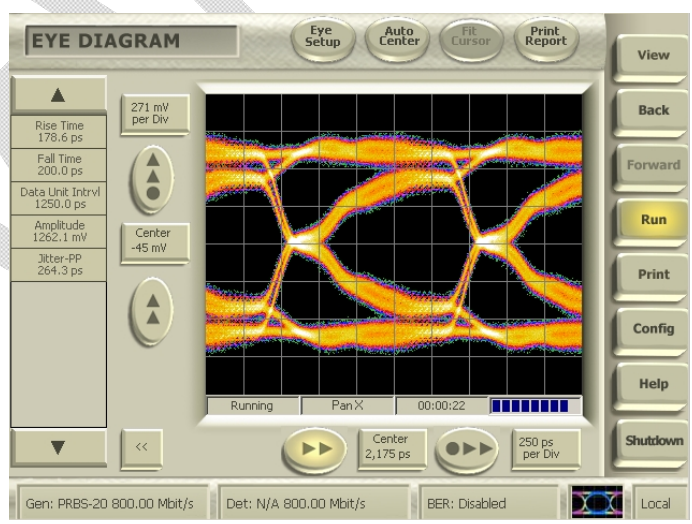

Figure 15: 800 Mbps Eye Pattern

These data all suggests that the 400 Mbps Baud rate predicted by table 5 is slightly conservative and the data rate 600 Mbps that is estimated by Figure 10 (-6 dB point) is the maximum rate that would be reliable.

Appendix 2*: Gigabit Ethernet*

As discussed on page 3, the bandwidth requirement of 1000 BaseT is very similar to the requirement of 100 Base T by design of the IEEE P802.3 task force. Both 100 and 1000 Base T have equal symbol rates of 125 Msymbols/s which produce the frequency spectrums shown in Figures 4 and 6. This commonality allows the use of existing CAT 5 cabling with GigE upgrades. However, since 1000 BaseT utilizes all 4 of the shielded pairs in the CAT 5 cable for bi-directional, full duplex data transmission (see Figure 17) , the Signal to Noise Ratio (SNR) overhead is normally degraded. Transmission line properties such as NEXT (near end crosstalk) and FEXT (far end crosstalk) noise, return loss noise, and signal attenuation all conspire to degrade the SNR headroom when 1000 BaseT Ethernet is transmitted across CAT 5 transmission line. This is not a significant problem except in cases where the channel length exceeds 50 m. It is important to incorporate a slip ring design that does not exacerbate this SNR degradation significantly.

In addition, introduction of a non-standard transmission line element such as a slip ring should introduce no significant phase delay between the signals in each of the four transmission lines which would produce signal jitter. As shown by Figure 24 the 1000 Base T eye pattern produced by the PAM-5 encoding scheme depends upon each of the twisted pair signals "lining up" in time.

The broadband slip rings discussed in pp 5-7 have the capability of transmitting 1000 BaseT data utilizing 9 copper rings. The techniques developed to control impedance and crosstalk for high speed data transmission prevent excessive (NEXT or FEXT) crosstalk noise as well as minimize return losses and signal attenuation. This broadband slip ring technology provides a very cost effective solution for transmitting multiple 1000 BaseT Ethernet lines.

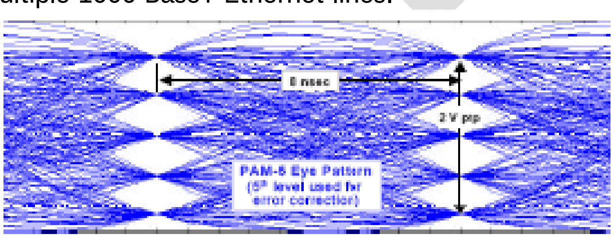

Figure 16: PAM-5 Eye Pattern (1000 Base T Ethernet)

The use of Ethernet data technology affords the possibility of utilizing standard switching and networking methodologies within the rotary joint to control "data traffic" in order to provide channel redundancy and reliability without increasing the number of data channels. Diagnostic and prognostic capabilities can also be introduced.

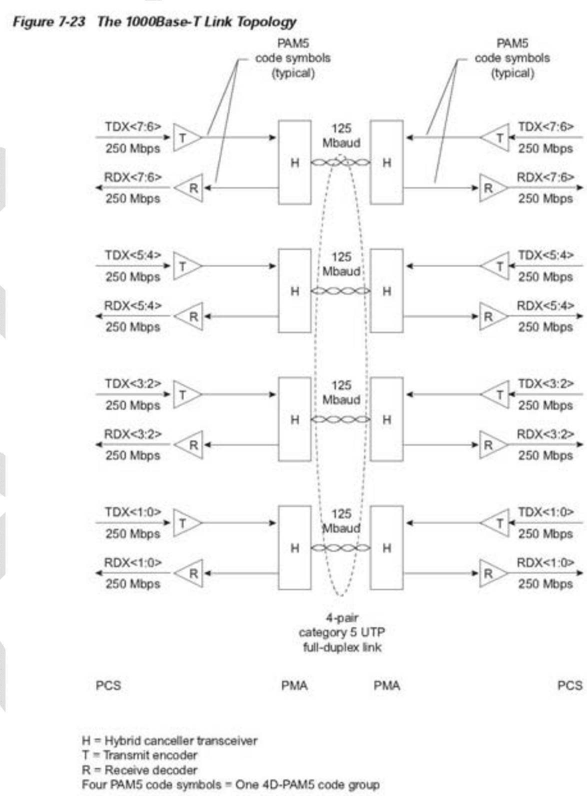

Figure 17: 1000 BaseT Transmission Scheme

Moog has several slip ring design options for transmitting 1000 BaseT on CAT 5, 6, or 7 cable through a slip ring on copper. The most common option is to use Moog's patented Broadband slip ring design for this data.